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AUTHOR: Michael G. Wilkins

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BIOLOGICAL COMPUTER LABORATORY

DEPARTMENT OF ELECTRICAL ENGINEERING, UNIVERSITY OF ILLINOIS, URBANA, ILLINOIS

A NEW HOMEOSTAT

by

Michael G. Wilkins
University of Illinois

BCL Report 8.3

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BIOLOGICAL COMPUTER LABORATORY
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ABSTRACT

The concept of homeostasis and its relations to control and regulation is briefly discussed and the ideas leading to the concept of the ultrastable hierarchic controller are sketched. Previous electronic realizations of homeostatic controllers are discussed, and a new homeostat is described briefly. The machine, presently under construction, has a number of new and useful features and these are described, together with experiments to be performed when the machine is complete.

HOMEOSTASIS AND HOMEOSTATS

Homeostasis, in the sense commonly employed in the field of biological computation*, is the cybernetic abstraction of the commonly occuring processes of regulation in real complex systems. By cybernetic abstraction is meant abstraction to the purely functional (or systems) level (see Pask, 1961; Ashby, 1960, for a fuller discussion). "Real complex systems" is usually taken to mean biological systems, but it can equally well mean social, psychological, etc. Homeostasis means more than just regulation. It means adaptive regulation or control, regulation of key or essential variables of the system--in other words, variables that must be kept within certain prescribed ranges in order to ensure the functional and/or structural integrity of the system.

Consider the simplest form of regulator, shown in schematic form in Figure 1. E is the environment with disturbances D, C is a controller attempting to maintain some variable x constant in the face of D, and f,g are the couplings between E and C. This simple type of controller is usually encountered when the nature of E is fully known, when D and its effects on x are understood and known and when the changes induced in x by D are not too "wild."

*As distinct from the purely physiological use of the term, which is generally somewhat narrower in its implications.

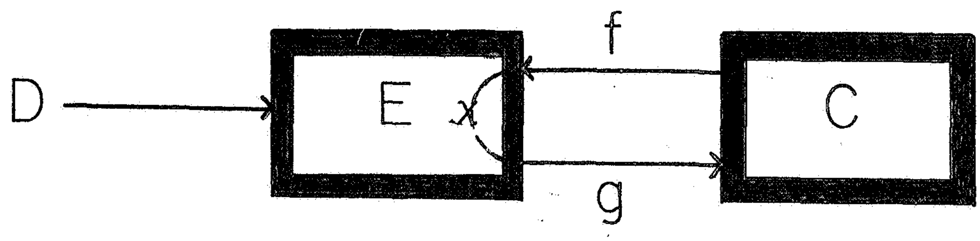

Figure 1

Now if C is not fully informed about the nature of E and D, and if the effects of D on x are liable to be drastic, it is advantageous for C to be able to change its mode of control of x. If C has been using method c_1 to control x, and if C starts to "lose control",if x is perturbed sufficiently to go outside its permissible range, then C could change its mode of control from c_1 to c_2, and on through c_3, c_4, etc., until it regains control of x, i.e., until x is once again brought within its permissible range. This is precisely what an adaptive controller does. The exact method of changing the mode of control of course, depends on the particular system. It can be mere variation of a parameter such as gain in the feedback loop, or it can be a radical change in the organization of C. This type of controller, the simple adaptive controller, can be represented schematically as in Figure 2.

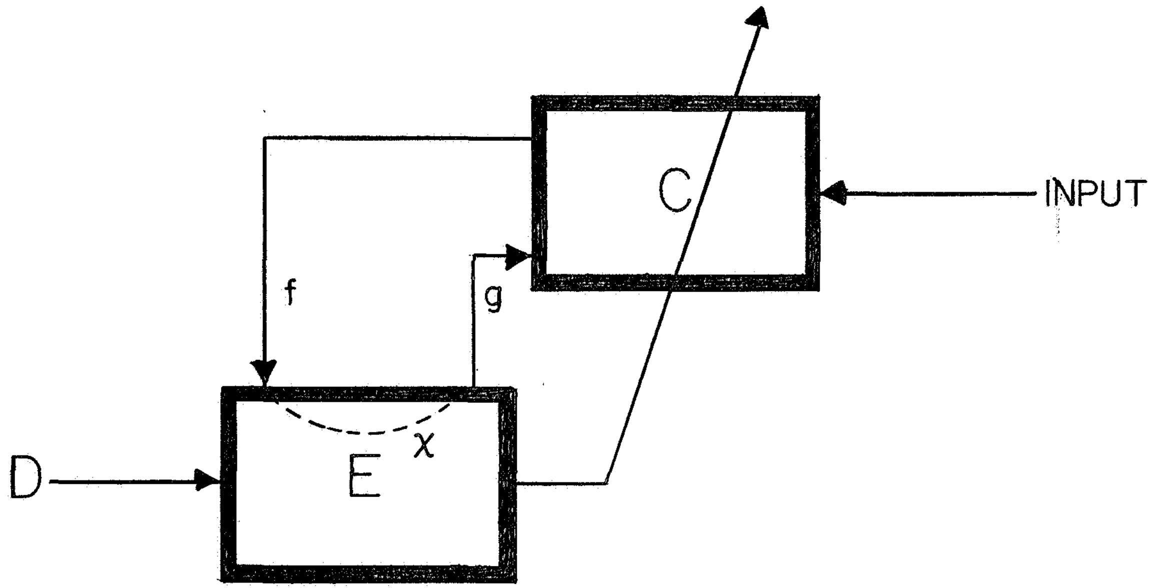

Figure 2

Here the arrow through box C, the controller, indicates change in the mode of operation of C. Figure 2 can be redrawn as in Figure 3. This system is now seen to be exceedingly similar to the "directive correlation" of Sommerhoff, (1950).

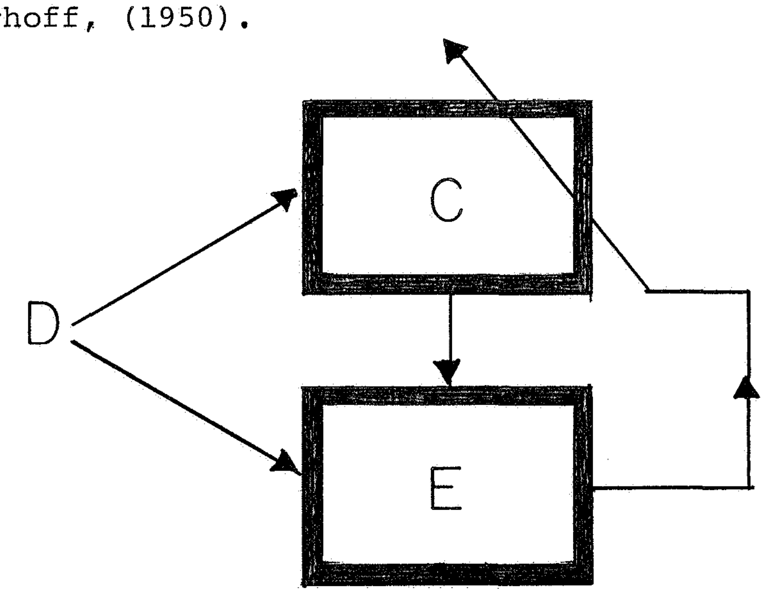

Figure 3

In Figure 2, the arrow leading into C and labeled "input" is the "set-point" or value of x that C is required to maintain. By careful choice of functions f and g, this can often be set equal to zero, and hence eliminated.

A simple example of an adaptive controller utilizing simple variation of gain is shown schematically in Figure 4. This is the Sperry adaptive autopilot. The function of the controller is to maintain aircraft attitude constant in the face of environmental perturbations by use of an actuator operating a control surface. However, changes in aircraft speed, air density, and other environmental parameters affects the stability of control. The relative stability of the actuator airframe system is continuously measured by the damping of the actuator, and the evaluative feedback loop adjusts the gain of the controller to maintain optimum damping. The study of adaptive control systems of this nature is of course a field in its own right, and is discussed in great detail in, for example, Mishkin and Braun, (1961).

An example of an adaptive regulator utilizing discontinuous changes in the mode of operation of C is the automatic gain control circuit in a sophisticated communications receiver. This system is shown schematically in Figure 5. The controller C contains the automatic gain control (AGC) circuits of the receiver, which forms the environment E. The AGC circuits, via the loop I, serve

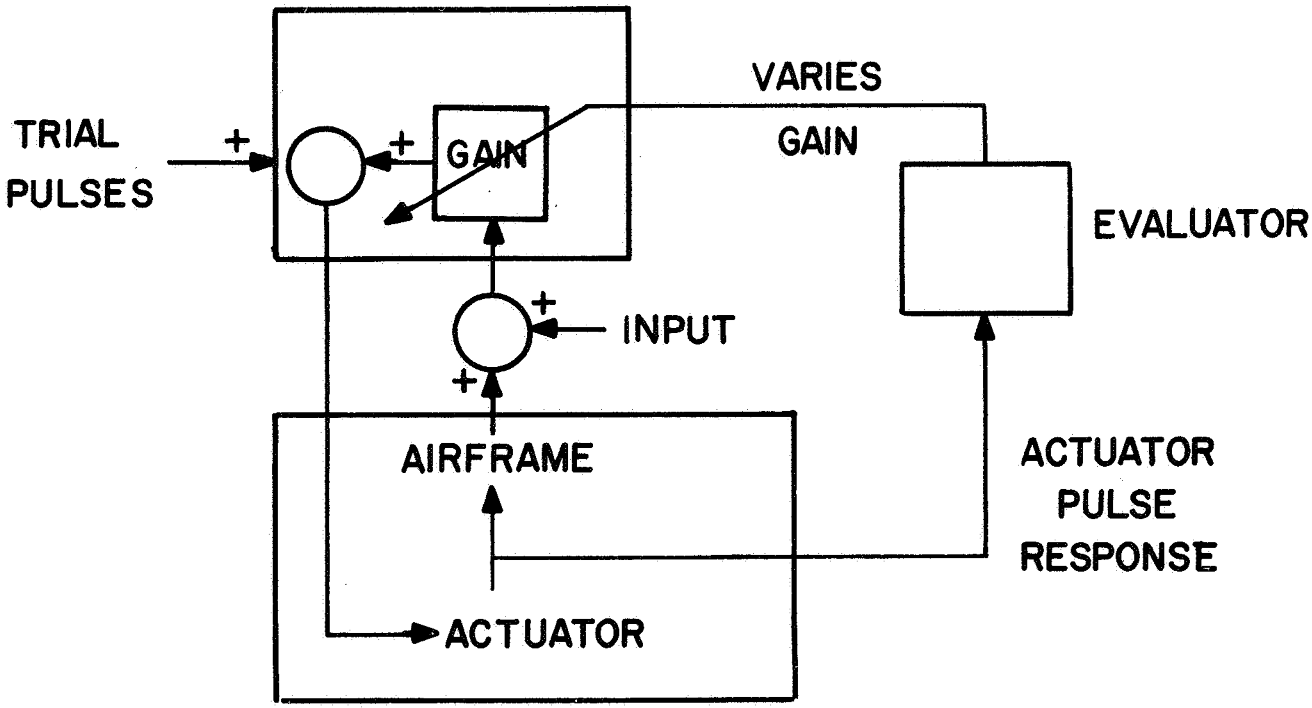
TRIAL
PULSES
+
+
GAIN
VARIES
GAIN
EVALUATOR
+
INPUT
+
AIRFRAME
ACTUATOR
PULSE
RESPONSE
ACTUATOR

Figure 4

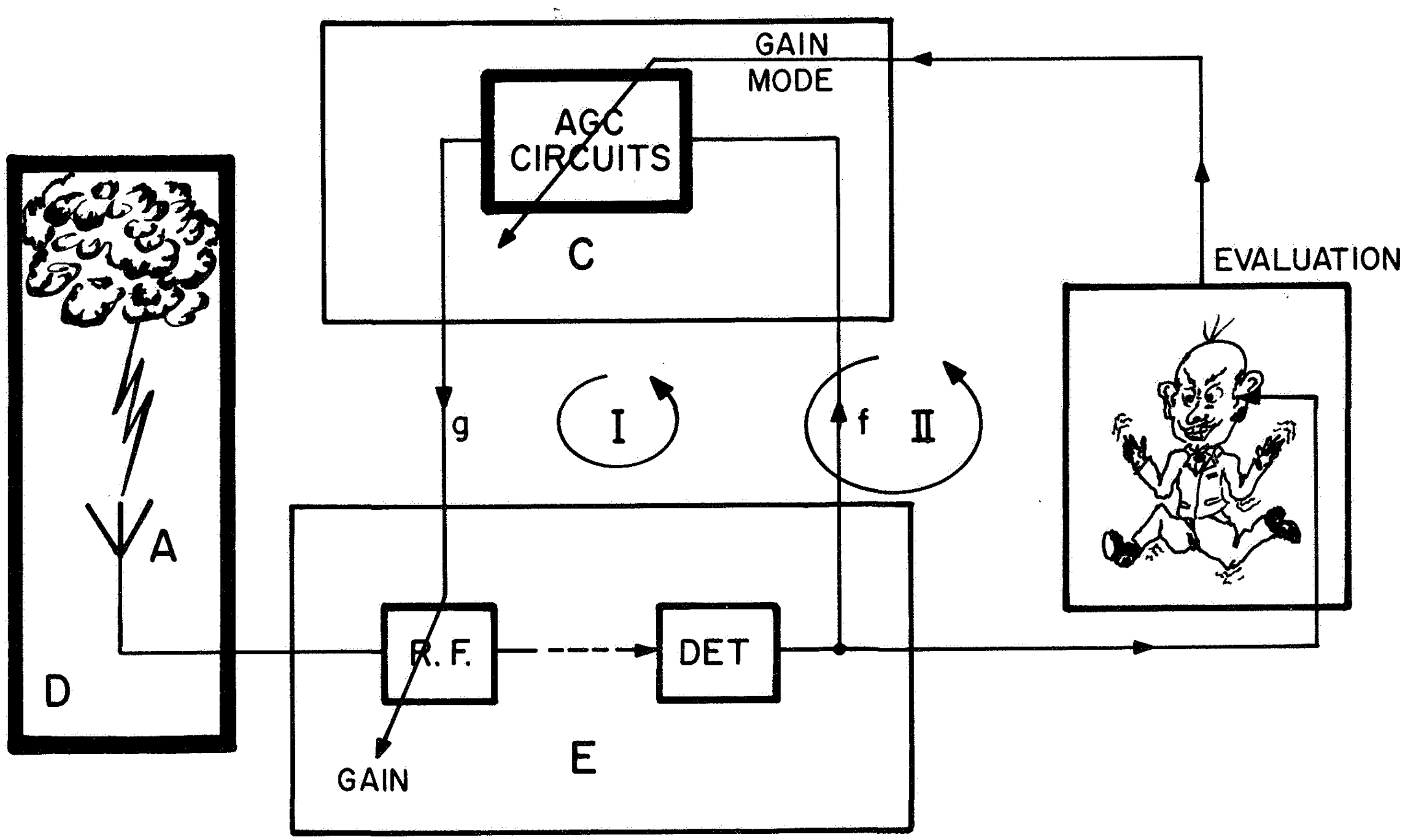

Figure 5

to maintain the detector output constant in the face of fluctuating signal strength at the antenna A. The receiver in E however, may have to receive many different types of signals, (CW, MCW, SSB, etc), and to do so and at the same time maintain constant output requires several different AGC circuits. The selection of the particular circuit used is under the control of the evaluative feedback loop II, a loop containing the operator. This loop also controls for drastic changes in the environment, changes due to extreme disturbances D.

As a final example it may be noted that some psychological theories invoke analogous mechanisms, (Freud; Miller, 1948). Direct expression is preferably utilized to keep the level of internal pressure or drive at some suitable value, and this control loop corresponds to loop I above. However, direct expression is often thwarted by the particular social and psychological environment, and in this case displacement or sublimation, or even more drastic measures such as repression or denial are employed. The type of control employed--direct expression, or displacement, or sublimation, etc.--corresponds to the evaluative loop II in the above examples.

The examples given above are obviously grossly oversimplified. What are the most obvious factors that have been neglected? Rather than deal with just one variable, a controller generally has to deal with a set of variables, all affected by D in different ways and to different degrees, and often interacting to varying extents. The adaptive or evaluative feedback may be different for each variable, requiring a multiplicity of type II loops. In such cases it is generally convenient to decompose C into a set of controllers C_1, C_2, ..., C_n, each attempting to regulate one of the variables x_1, x_2, ... , x_n. This is shown schematically in Figure 6. Here evaluative feedback is regarded as being fed to each controller directly, but more generally it may be regarded as input to a "supercontroller" C, which in turn regulates the C_i as in Figure 7. The system in Figure 6 is, in Ashby's parlance, the general ultrastable* system. That of Figure 7 may be extended to the most general adaptive controller of all, the general hierarchic ultrastable system, Figure 8. This is a hierarchy of controllers, sometimes termed a multi-stable system or controller. At any level of control L_j, events occur in some metalanguage, as distinct from the object language occuring in the real environment. The "environment" of level L_j is just the level of controllers immediately below L_j, and it is in this "environment" that L_j attempts to control disturbances.

*As distinct from polystable, which only refers to a system with many equilibrial states, making no reference to control, feedback, or evaluation.

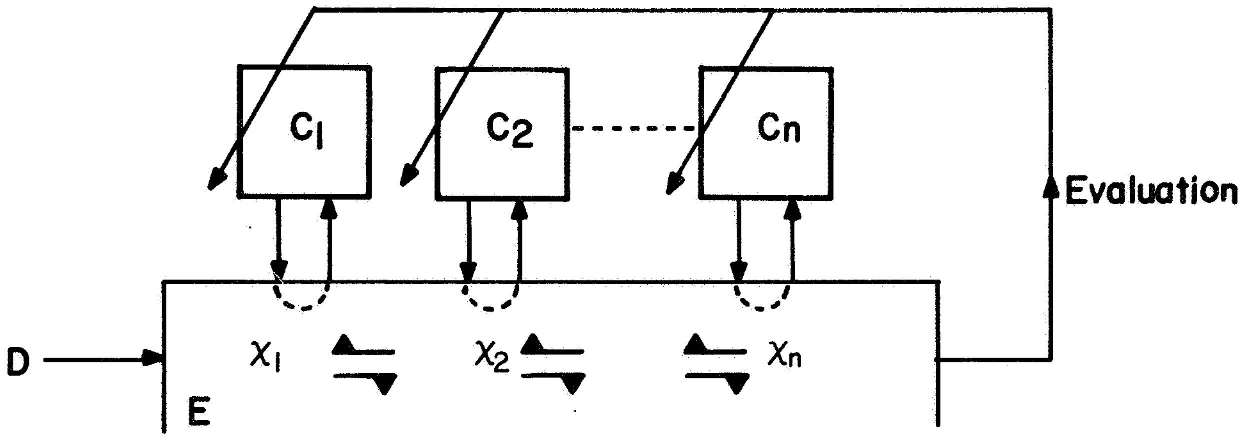

Figure 6

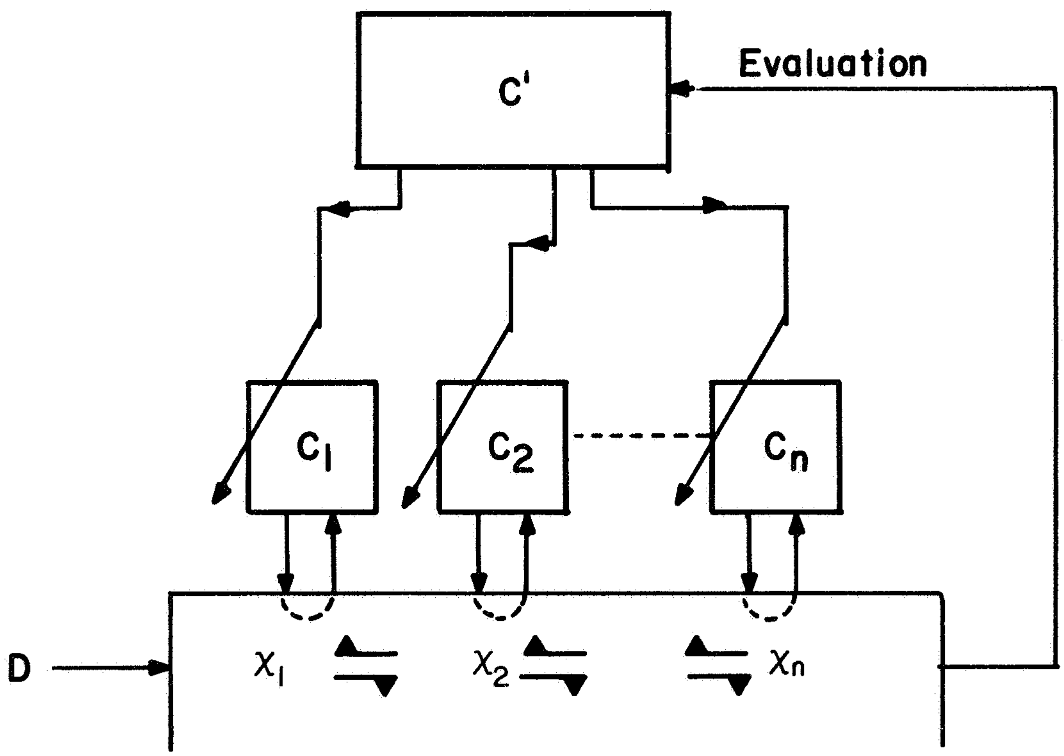

Figure 7

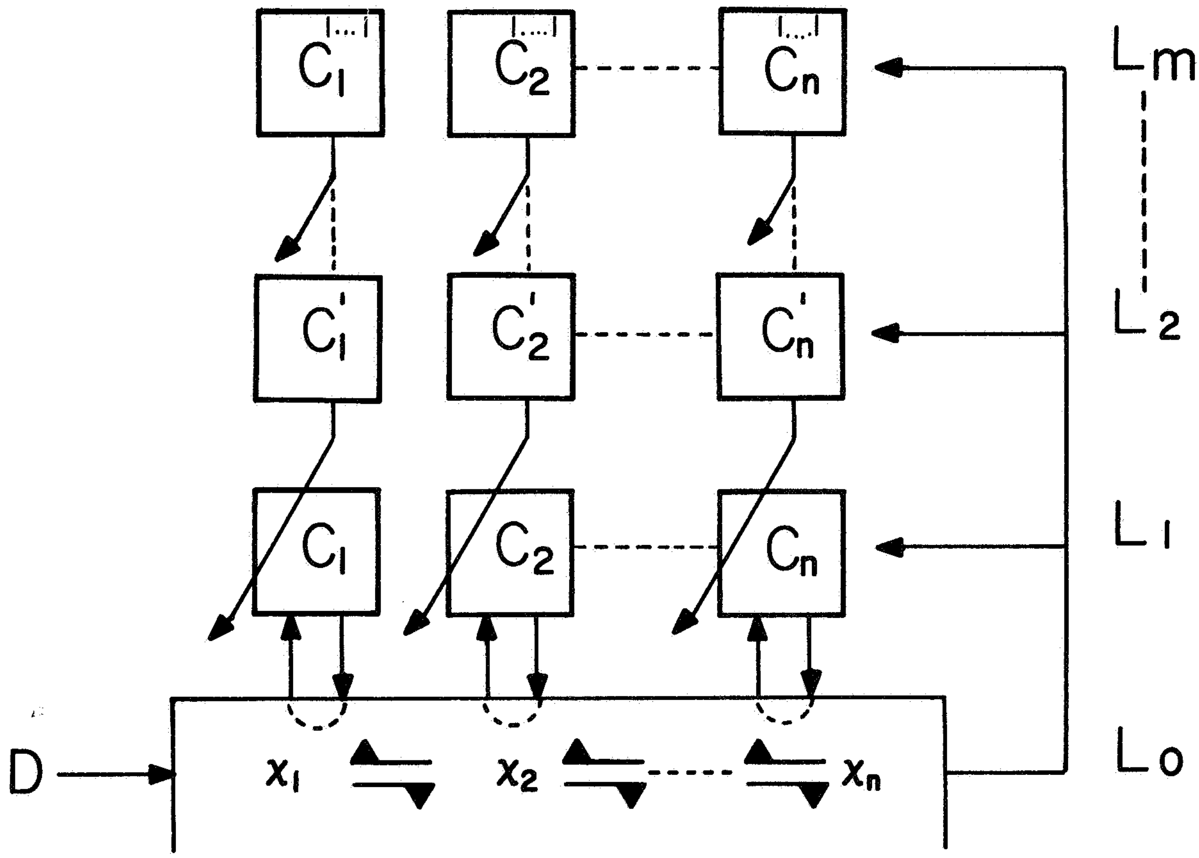

Figure 8

Now let us return to the simplest ultrastable system, Figure 2. The artefacts* called homeostats arise from this particular conceptualization of adaptive control. Specifically, the first homeostat constructed, that of Ashby (1948, 1960), was a device for examining and displaying ultrastable control and behavior. It consisted of four basically linear first order servomechanisms that could be interconnected in a variety of ways, each servo having variable parameters (essentially signed gain). One unit of the identical four is shown schematically in Figure 9.

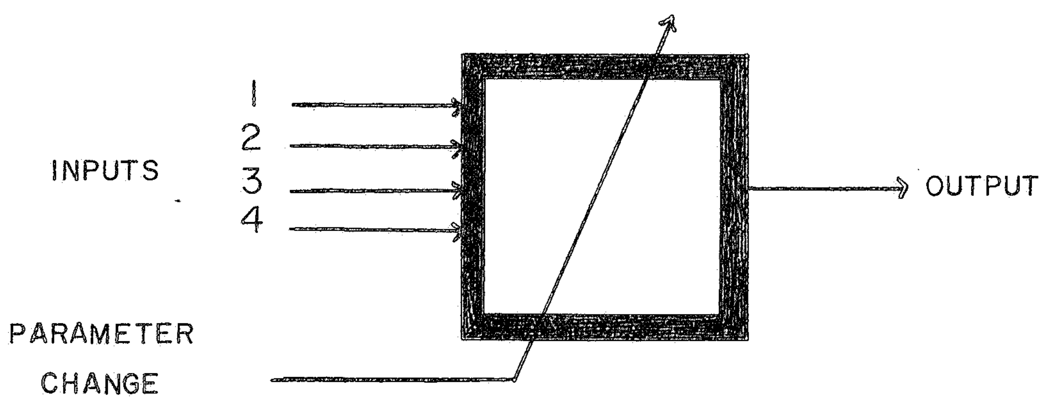

Figure 9

Adaptive change in the mode of control of each unit was achieved by allowing the outputs of some units to affect the parameters of others in non-linear fashion. The parameters, in fact, were made to change discontinuously

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*Artefact in the sense of a man-made, physically realized device or machine, not in the sense of something spurious (but we grant that the distinction is sometimes blurred).

whenever selected outputs exceeded some preset value. Ashby's homeostat was capable of demonstrating most of the behaviors to be expected from a first-order ultrastable controller (see Ashby,1960, for full details). However, adaptive variation in the mode of operation of the controllers could only proceed by discontinuous variation of parameters, and not at some deeper level such as qualitative change in transfer function. Further, the machine was incapable of being connected in a true hierarchic fashion. The value of variable at which parameter change was initiated was permanently fixed, and could not be modified by another unit.

Two other homeostats are discussed in the literature--that of Haroules <u>et al</u> (1960) and the device constructed by Zemanek (1958). Haroules machine was originally developed in connection with an FAA air traffic control research program, and was essentially similar to Ashby's. The only difference was in the number of units, 16 compared to the four of Ashby. Very little work was done with this machine; a few static and dynamic responses were determined before the program was apparently terminated. The homeostat constructed by Zemanek appears to be identical to Ashby's, the only difference being in its use. An attempt was made to couple the device to an external environment, and while interesting, was apparently never pursued in detail.

WHY A NEW HOMEOSTAT?

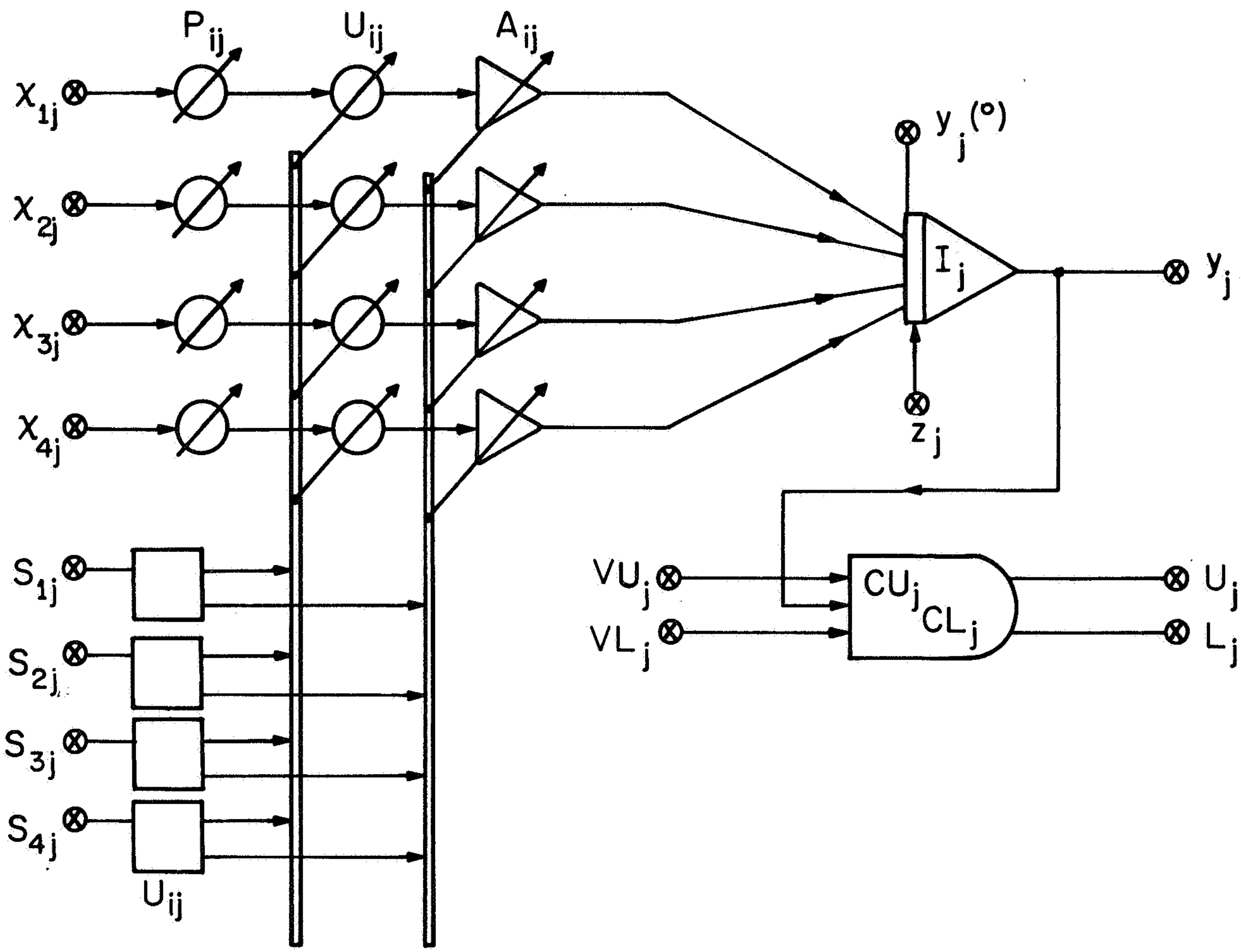
a. Why not!

b. A readily programmed and flexible machine would be of great use as a teaching instrument. Such a machine should allow immediate visualization of phase plane behavior, and should provide for simple and effective control of all system parameters. It must of course be capable of demonstrating all the basic properties of simple ultrastable and adaptive systems; i.e., it must do all that Ashby's machine did. It would be advantageous if the device was capable of demonstrating the properties of simple hierarchies of adaptive controllers, (Pask, 1961), and could readily be coupled to some external environment.

c. With the recent development of inexpensive integrated circuit operational amplifiers it has become possible to construct a relatively inexpensive yet precise voltage analog, with the accompanying simplicity of readout and connection. This method of construction also allows for repetitive automatic operation, and the investigation of a variety of linear and nonlinear transfer functions.

THE PROPOSED MACHINE

The proposed and partially completed machine is shown in part in Figure 10. This figure shows one of four identical units making up the machine; only signal flow paths are included. Each unit essentially computes the following:



P_{ij}
U_{ij}
A_{ij}
X_{1j}
X_{2j}
X_{3j}
X_{4j}
$y_j(°)$
I_j
y_j
z_j
S_{1j}
S_{2j}
S_{3j}
S_{4j}
U_{ij}
VU_j
VL_j
CU_j
CL_j
U_j
L_j

Figure 10

$$y_j(t) = k \int_0^t \sum_i a_{ij}(t) x_{ij}(t) dt + y_j(0)$$

where for the jth. unit, $y_j(t)$ is the output at time t; $x_{ij}(t)$ are up to 5 inputs; $y_j(0)$ is a constant; k is a constant, and $a_{ij}(t)$ are gains dependent upon time in a generally discontinuous manner.

The jth. unit possesses four inputs x_{ij} derived from other parts of the system or from the jth. unit; it also has one input z_j for inputs from external sources. Manual attenuation for each channel is provided by potentiometers p_{ij} that can be switched in or out of circuit. Automatic random attenuation is provided by potentiometers r_{ij}, switched by uniselectors U_{ij}. Stepping commands to the U_{ij} are inputs s_{ij}. The U_{ij} also automatically switch in and out of circuit the inverting amplifiers A_{ij}, (which can be manually controlled, if so desired). The r_{ij} and A_{ij} provide the step-functions, (Ashby, 1960). In reality, in the prototype machine the U_{ij} will all be part of one selector U_j, with 25 positions as in Ashby's machine, therefore yielding 25^4 states for the whole machine. The system will later be modified by effectively adding more positions to U_j, increasing the possible number of machine states to about 10^8. Another more interesting modification will be to add 3 more selectors per unit, making the switching in the four input channels independent, and yielding approximately 10^{10} states maximum, (far fewer in practice due to the small number of different resistances available--but see the discussion below).

The attenuated and possibly inverted signals are added and integrated by the operational amplifier integrator I_j. Output y_j is taken from this unit. Initial conditions $y_j(t)$ may be set on I_j by relay circuits, either manually or automatically. The integration time constant may be readily changed, thus time-scaling the integrator. In practice p_{ij} and r_{ij} will be part of the resistor network of I_j.

The output of the unit, y_j, is fed to two comparators CU_j and CL_j. These devices produce signals whenever y_j exceeds VU_j or falls below VL_j, where VU_j and VL_j are limit levels that can vary over the entire dynamic range of the machine. The comparators can either monitor y_j continuously, or sample it at some preset regular interval, or even randomly. Normally the signals produced by the operation of the comparators, indicating that y_j has exceeded some limit, are used to step the uniselectors in the same or another unit. The limit levels VU_j and VL_j can either be manually preset, or obtained from other outputs y_k. They can even be derived from events in the external environment of the machine.

All connections to the four units are on a patch board on the machine control panel, and are also available via connectors. Each unit separately, or the whole machine, may be set to a predetermined initial state at any time, therefore allowing cycling through some given behavior. All signals are available in a suitable form for driving displays such as X-Y plotters or a CRT.

USES AND APPLICATIONS

The prototype machine will have one uniselector per unit, with 25 positions per uniselector. This will yield a maximum of 380,625 machine states, as in Ashby's homeostat. The machine will be used to demonstrate the behaviors discussed by Ashby in Design for a Brain, and to explore related phenomena in small ultrastable systems. It is hoped to make the system available to students in the author's course on Biological Computation, and it will certainly be used for demonstration purposes in that course where appropriate.

In this system it is particularly simple to provide rather complicated constraints in the phase plane, just by incorporating several different comparators connected by simple logic circuits, the comparators being fabricated from diode and transistor function generators. Figure 11 shows some possible constraints or critical regions in a two-variable phase plane, constraints and regions that can be synthesized electronically in a simple fashion. The behaviors of the ultrastable system under a variety of

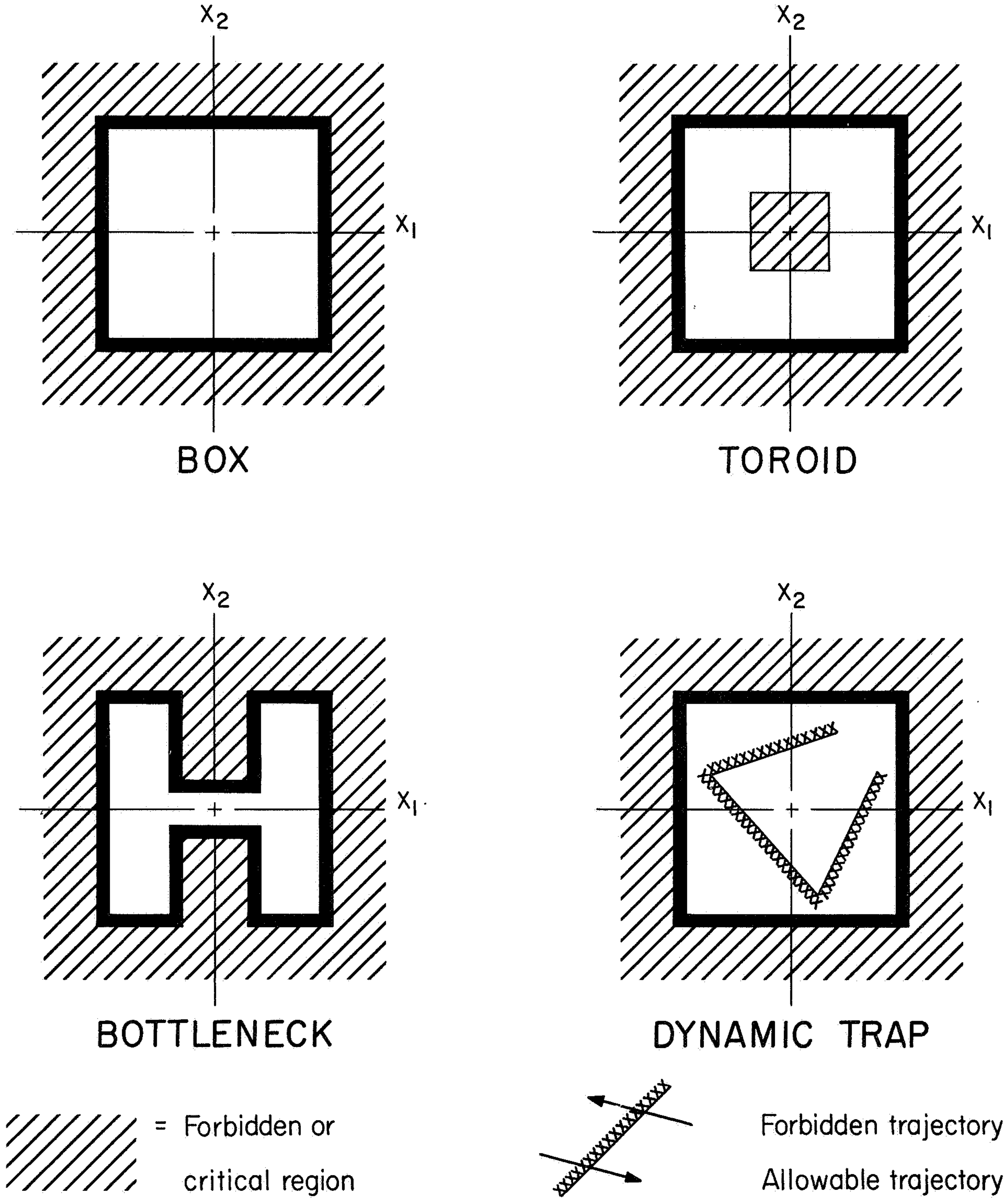


FIGURE 11

Figure 11

more or less peculiar constraints will be examined.

Some or all of the critical regions and constraints can be controlled by the machine itself; for example, by deriving a CL_j or CU_j from a y_k. The machine can therefore not only change its own mode of behavior, but change the region within which it can operate. A particularly interesting case is shown in Figure 12 below.

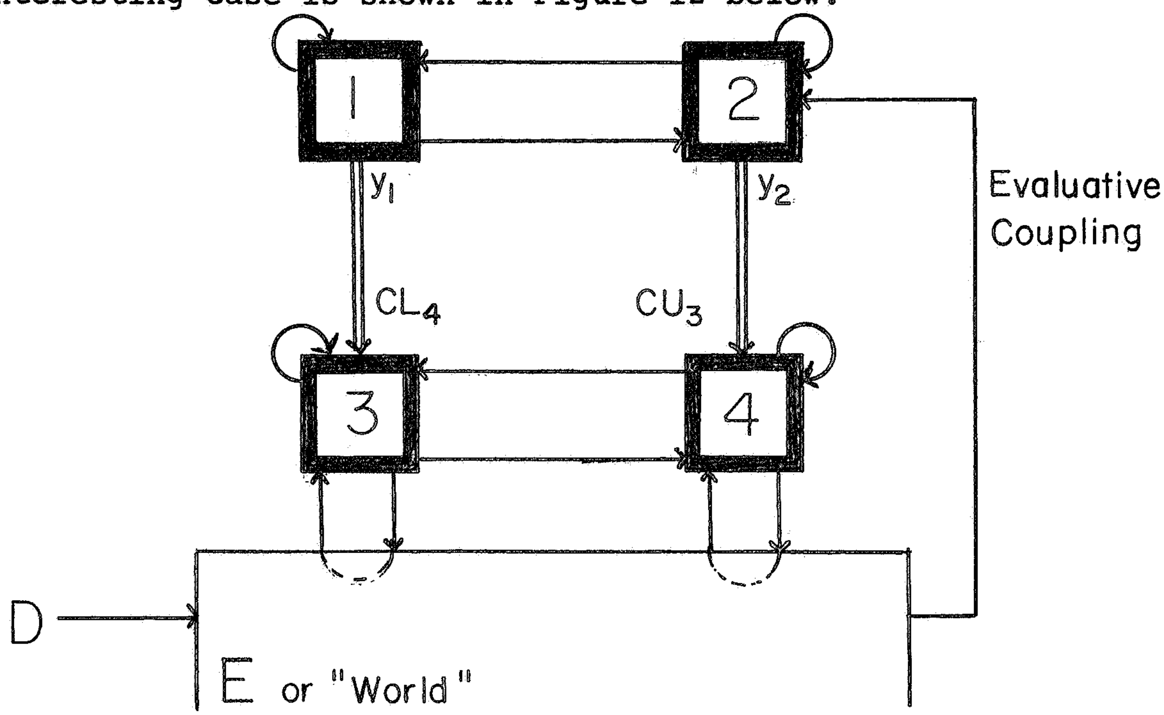


Figure 12

Here the system is organized in a hierarchy, and is actually a special case of the hierarchic ultrastable controller discussed by Pask (1961, for example). Events in the "world" of the system, i.e., perturbations introduced by the operator, and the recorder pen position, are in the object language. Events in units 3 and 4 are in metalanguage L_1, and events in units 1 and 2 are in metalanguage

L_2. Units 3 and 4 form a subcontroller or subcontrollers, having their critical regions set by the master controller 1 and 2. The evaluative coupling E can be derived from the "world" as, say, the average disturbance over some period of time, or as the average number of uniselector transitions in units 3 and 4 per unit time.

It is of interest to the author to couple the system, organized in a hierarchic fashion, to some artefact in the real world such as Grey Walter's M. Docilis or M. Speculatrix, or a mutation thereof. This has been suggested, but to the author's knowledge never been tried, (Zemanek 1958).

As mentioned above, the number of states of the system can be increased enormously, merely by adding some minor circuits. There is little reason to do this for its own sake, as there is a limit to the number of different resistors available for the attenuators, and all variables can only be measured and recorded to a certain accuracy. Further, an increased number of states will only greatly lengthen the average convergence time to stability. However, the total number of states, about 10^8, can be divided into subsets, and to each subset can be attached a certain transfer function, usually nonlinear. Within each subset the numerical values of gain will be selected randomly, as in the machine with fewer states. The subset selection will also be on a random basis, but will be controlled from a different source. For example, in the hierarchic machine of Figure 11, units 1 and 2 (the master controller) will select the subset of transfer functions used in units 3 and 4 (the subcontrollers). The subcontrollers themselves will select the actual gain used within a given subset of transfer functions. So the master controller selects the overall way that the subcontrollers regulate themselves and the world, thereby providing some measure of control over drastic changes in the world. Figure 13 shows some subsets of simple transfer functions. In each diagram, V_2 is output and V_1 is input, and p is the parameter selected by the subcontrollers.

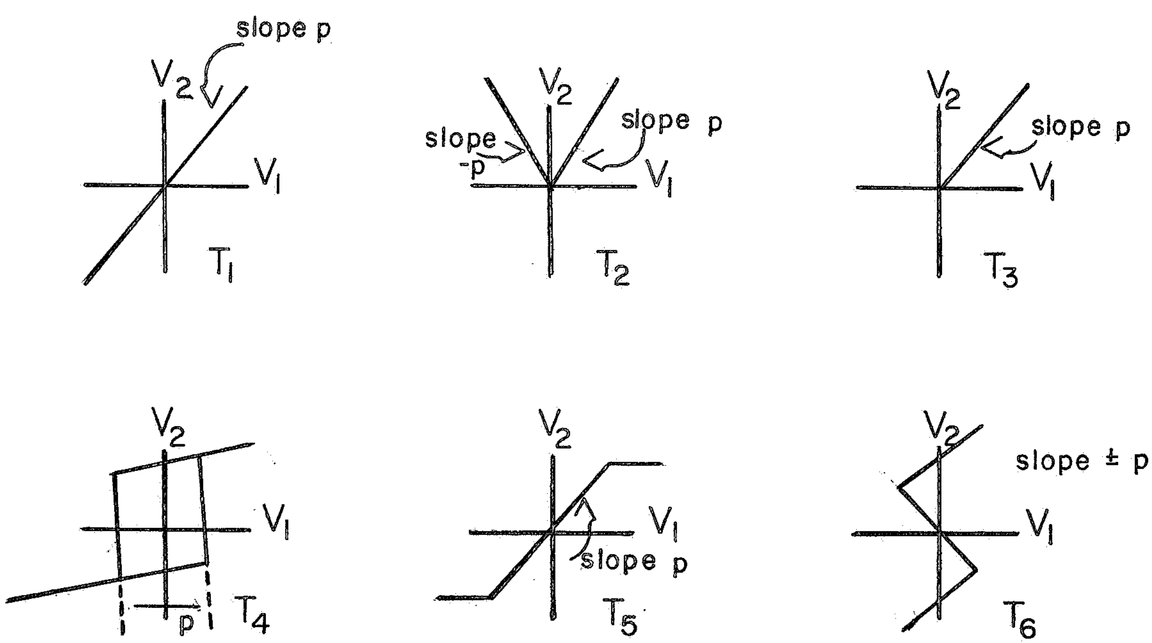


Figure 13

PROGRESS TO DATE

All mechanical work is essentially complete, and all DC switching circuits have been wired. All major patch board and control wiring is complete, together with associated monitor circuitry.

WORK NECESSARY TO COMPLETE

The next stage in the construction of the system is the design and fabrication of the operational amplifier circuitry. This consists of the inverting amplifiers A_{ij}, integrators I_j, and comparators CU_j and CL_j. No difficulty is anticipated as the circuitry utilizes completely standard analog computer techniques.

The final stage will be the assembly of built-in power supplies, and the connection of the separate panels. It is anticipated that the system will be substantially complete and operating at least at a primitive level in a few months.

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